

Direct searches for the standard model Higgs boson produced in association with a vector boson at CDF

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We present the results of searches for the standard model Higgs boson at CDF in final states with bottom quarks. Results are derived from the complete Tevatron Run II dataset, with a measured integrated luminosity of 9.5 fb^{-1} of proton-antiproton data. The searches are performed for assumed Higgs masses between 90 and 150 GeV, for Higgs bosons produced in association with W or Z bosons. Employing several improved techniques, these are currently the most sensitive searches in the world for these processes, surpassing previous CDF results by 30% beyond what would be expected from the addition of new data alone. Combining the search sensitivity of these production modes, 95% upper confidence limits on the standard model cross section times branching fraction are derived, yielding an observed (expected) upper limit of 4.3 (1.8) times the standard model prediction for a 125 GeV Higgs boson. The significance of the data relative to the background-only hypothesis is 2.5 sigma.

*36th International Conference on High Energy Physics,
July 4-11, 2012
Melbourne, Australia*

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1. Introduction

Understanding the mechanism for electroweak symmetry breaking, especially by testing for the presence or absence of the standard model (SM) Higgs boson [1], has been a major goal of particle physics and a central part of the Fermilab Tevatron physics program. Both CDF and D0 collaborations have performed direct searches for the standard model Higgs boson [2]. The new searches reported here include more data, additional channels, and improved analyses techniques compared to previous analyses. Results are derived from the complete Tevatron Run II dataset, with a measured integrated luminosity of 9.5 fb^{-1} of proton-antiproton data. The searches are performed for assumed Higgs masses between 90 and $150 \text{ GeV}/c^2$.

The SM does not predict the mass of Higgs boson, m_H , but the global fit of the electroweak precision data, including recent top-quark and W boson mass measurements from the Tevatron [3, 4], constrains m_H to be less than $152 \text{ GeV}/c^2$ at the 95% confidence level (CL) [5]. The direct searches from LEP [6], Tevatron [2], and LHC results [7, 8] set the Higgs mass between 116.6 and $119.4 \text{ GeV}/c^2$ or between 122.1 and $127 \text{ GeV}/c^2$ at the 95% CL. Recently both LHC experiments [9, 10] observed local excesses above the background expectations for a Higgs boson mass of approximately $125 \text{ GeV}/c^2$. Much of the power of the LHC searches comes from $gg \rightarrow H$ production and Higgs boson decays to $\gamma\gamma$, W^+W^- , and Z^+Z^- , which probe the couplings of the Higgs boson to other bosons. In the allowed mass range, the Tevatron experiments are particularly sensitive to the associated production of the Higgs boson with a weak vector boson in the $b\bar{b}$ channel, which probes the coupling of the Higgs boson to b quarks.

The Tevatron collider produces proton and anti-proton collision at the center mass of 1.96 TeV with a record luminosity of $4.3 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. The Tevatron delivered close to 12 fb^{-1} to each experiment before the shutdown on 30 September 2011. The CDF detector is a general-purpose detector, which provides excellent tracking, lepton identification, jets finding, missing transverse energy (\cancel{E}_T) detection, and efficient multilevel triggers. The details can be found elsewhere [11].

2. Search Strategies

The dominant Higgs production processes at the Tevatron are the gluon-gluon fusion ($gg \rightarrow H$) and the associated production with a W or Z boson [12]. The cross section for WH production is twice that of ZH and is about a factor of 10 smaller than $gg \rightarrow H$. The Higgs boson decay branching fraction is dominated by $H \rightarrow b\bar{b}$ for the low-mass Higgs ($m_H < 135 \text{ GeV}/c^2$) and by $H \rightarrow W^+W^-$ or ZZ^* for the high-mass Higgs ($m_H > 135 \text{ GeV}/c^2$). A search for a low-mass Higgs boson in the $gg \rightarrow H \rightarrow b\bar{b}$ channel is extremely challenging because the $b\bar{b}$ QCD production rate is many orders of magnitude larger than the Higgs boson production rate. Requiring the leptonic decay of the associated W or Z boson greatly improves the expected signal over background ratio in these channels. As a result, the Higgs associated production with $H \rightarrow b\bar{b}$ is the most promising channel for the low-mass Higgs boson searches at the Tevatron.

The search strategies employed at CDF have been evolving constantly over time. We first maximize the signal acceptance by using efficient triggers, excellent lepton identifications, and powerful b -tagging, which can improve the signal to background ratio up to the 1% level. Then we use multivariate analysis (MVA) to exploit the kinematic differences between signal and back-

ground, which can further enhance the signal to background ratio up to the 10% level in the high score regions. The same strategies have been used to help discover the single-top and diboson processes at the Tevatron, and provide a solid ground for isolating a small signal out of a large background.

For the $H \rightarrow b\bar{b}$ signatures we look for a $b\bar{b}$ mass resonance produced in association with a W or Z boson where W decays into lv or Z decays into l^+l^- or $\nu\bar{\nu}$. The $WH \rightarrow lvb\bar{b}$ is the most sensitive channel that gives one high P_T lepton, large \cancel{E}_T , and two b -jets. Before b -tagging, the sample is predominated by the W + light-flavor jets, which provides an ideal control data to test the background modeling.

Since there are two b -quark jets from the low-mass Higgs decay, improving b -tagging is crucial. CDF use multivariate b -taggers to exploit the decay of long-lived B hadron as displaced tracks/vertices. The typical b -tag efficiency is about 40-70% with a mistag rate of 1-5% per jet. Recently CDF combined their existing b -taggers into a Higgs Optimized b -tagger (HOBIT) [13] using a neural network tagging algorithm, based on sets of kinematic variables sensitive to displaced decay vertices and tracks within jets with large transverse impact parameters relative to the hard-scatter vertices. Using an operating point which gives an equivalent rate of false tags, the new algorithm improves upon previous b -tagging efficiencies by $\approx 20\%$.

3. $H \rightarrow b\bar{b}$ Searches

We describe the searches for the low-mass Higgs boson with $H \rightarrow b\bar{b}$ at CDF.

3.1 $WH \rightarrow lvb\bar{b}$

One of the golden channels for the low-mass Higgs boson search at the Tevatron is the Higgs produced in association with a W boson with $WH \rightarrow lvb\bar{b}$ [14]. We select events with one isolated high P_T lepton (electron, muon, or isolated track), a large missing transverse energy, and two or three jets, of which at least one is required to be b -tagged as containing a weakly-decaying B hadron. Events with more than one isolated lepton are rejected. For the multivariate discriminant, we train a Bayesian neural network discriminant (BNN) in the W + two or three jets for each Higgs mass, separately for each lepton type, jet multiplicity, b -tagging category.

We perform a direct search for an excess of events in the signal region of the final discriminant from each event category. Since there is no significant excess of signal events observed in the data, we set an upper limit at 95% CL on the Higgs production cross section times branching ratio with respect to the SM predictions as a function of Higgs mass. CDF set an observed (expected) upper limit at 4.9(2.8) for $m_H = 125 \text{ GeV}/c^2$.

3.2 $ZH \rightarrow l^+l^-b\bar{b}$

Another interesting channel to search for the low-mass Higgs boson is $ZH \rightarrow l^+l^-b\bar{b}$ [15]. It has a clean signature, but a low event yield due to a small branching fraction of $Z \rightarrow e^+e^-$ and $\mu^+\mu^-$. We select events with two high P_T leptons from Z decay and two or three jets. Events are further divided based on lepton type, jet multiplicity, and the number of b -tagged jets, similar to $WH \rightarrow lvb\bar{b}$. To increase signal acceptance we use neural networks to select loose dielectron and dimuon candidates. The jet energies are corrected for the missing E_T using a neural network

approach. We utilize a multi-layer discriminant based on neural networks where separate discriminant functions are used to define four separate regions of the final discriminant function. There seems to be an excess of events in the high score signal region, but nothing statistically significant yet. We set an observed (expected) upper limit at 95% CL on the Higgs cross section times branching ratio over the standard model prediction at 7.2 (3.6) for the Higgs mass at 125 GeV/c².

3.3 $WH, ZH \rightarrow \cancel{E}_T b\bar{b}$

We also search for the Higgs boson in the ZH and WH channels where the Z boson decays into two neutrinos or the lepton from the W decay is undetected [16]. It has a large signal rate as well as a large QCD-multijet background. However, the final state is relatively clean, containing two high E_T jets and a large missing transverse energy. We require $\cancel{E}_T > 50$ GeV and two b -tagged jets. We use a track-based \cancel{E}_T calculation as a discriminant against false \cancel{E}_T . In addition we utilize a neural network to further discriminate against the multi-jet background. The final discriminant is obtained for a Higgs signal by combining dijet mass, track \cancel{E}_T , and other kinematic variables. The data are consistent with the background expectations; we set an observed (expected) upper limit at 95% CL on the Higgs cross section times branching ratio over the standard model prediction at 6.8 (3.6) for the Higgs mass at 125 GeV/c².

4. Combination of $H \rightarrow b\bar{b}$

We combine searches for $H \rightarrow b\bar{b}$ in three most promising channels, and set limits with respect to nominal SM predictions [17]. We combine the results using a combined likelihood formed from a product of likelihoods for the individual channels. Systematic uncertainties are treated as nuisance parameters with truncated Gaussian. The common systematics between channels are the luminosity, detector related efficiencies, theoretical cross sections, and PDF uncertainties, which are treated as correlated. The instrumental backgrounds are treated as independent. Most of nuisance parameters are well constrained by the data in the dominant background region and are not very sensitive to the initial-input values.

To validate our background modeling and search methods, we additionally perform a search for $Z \rightarrow b\bar{b}$ in association with a W or Z boson using the same final states of the SM $H \rightarrow b\bar{b}$ searches. The data sample, reconstruction, background models, uncertainties, and sub-channel divisions are identical to those of the SM Higgs boson search, but the discriminant functions are trained using the signal of $Z \rightarrow b\bar{b}$ instead. The measured cross section of $WZ + ZZ$ is 4.1 ± 1.3 pb, which is consistent with the SM prediction of 4.4 ± 0.3 pb.

To further check the consistency between data and background, we rebin the final discriminant from each channel in terms of the signal to background ratio (s/b) so that the data with similar s/b may be added without loss of sensitivity. The resulting data distributions after background subtraction are shown in figure 1 (left) and compared to the expected signal of $m_H = 125$. There seems to be a small excess of Higgs boson candidate events in the highest s/b bins relative to the background-only expectations.

Figure 1 (right) shows the combined limit of $H \rightarrow b\bar{b}$ after combining three channels together. We start to exclude the Higgs mass near the low-mass end between $90 < m_H < 96$ GeV/c² and obtain an observed (expected) limit of 4.15 (1.8) at 95% CL on the SM Higgs production cross

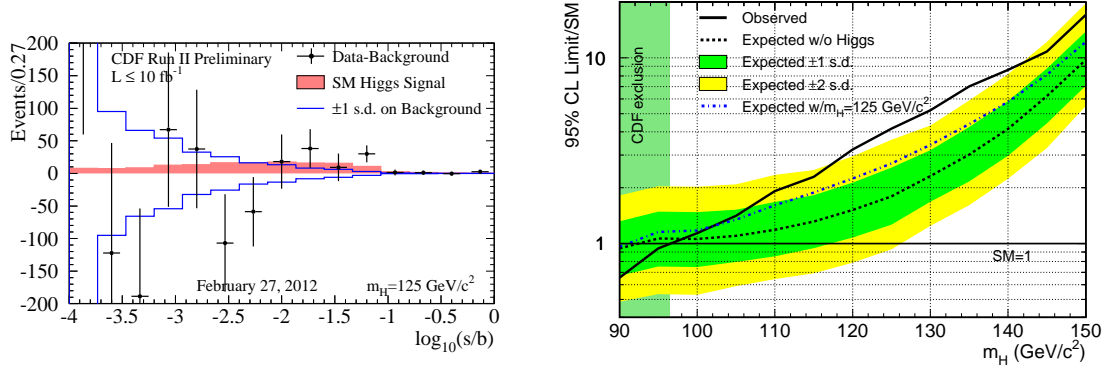


Figure 1: (Left) Background-subtracted data distributions for the discriminant histograms, summed for bins with similar s/b , for $m_H = 125 \text{ GeV}/c^2$. (Right) Observed and expected 95% CL upper limits on SM Higgs boson production cross section with respect to SM predictions as a function of m_H . The shaded bands indicate the one or two sigma regions where the limit is expected to fluctuate, in the absence of signal. The dot-dashes are the expected limits with the SM Higgs signal of $m_H = 125 \text{ GeV}/c^2$.

section with respect to the SM prediction for $m_H = 125 \text{ GeV}/c^2$. There seems to be a small excess of events between 115 and 140 GeV/c^2 . We quantify the excess by calculating the local p-value for the background-only hypothesis. Figure 2 (left) shows the local p-value as a function of Higgs mass where the solid curve is for data and the dashed curve is what is expected from the SM Higgs production of $m_H = 125 \text{ GeV}/c^2$. At $m_H = 135 \text{ GeV}/c^2$, we have a minimum local p-value=0.32% or 2.7 sigma, which corresponds to a global p-value=2.5 sigma including a LEE factor of 2. Given the excess we also fit the signal cross section times the decay branching ratio as a function of Higgs mass as shown in Figure 2 (right). We measure an associated production cross section times the decay branching ratio of $(\sigma_{WH} + \sigma_{ZH}) \times B(H \rightarrow b\bar{b}) = 291_{-113}^{+118} \text{ (stat+sys) fb}$, which is consistent with the SM prediction of $120 \pm 10 \text{ fb}$ for $m_H = 125 \text{ GeV}/c^2$.

5. Conclusion

In conclusion, with a full dataset and many years of hard work, the CDF Collaboration has finally exceeded their most optimistic sensitivity projection based on 2007 summer results. The searches are conducted for a Higgs boson that is produced in association with a W or Z boson, has a mass in the range 90-150 GeV/c^2 , and decays into $b\bar{b}$ pair. We observe an excess of events in the data compared with the background predictions, which is most significant in the mass range between 115 and 135 GeV/c^2 , consistent with the Higgs-like particle recently observed by ATLAS and CMS. The most significant local excess is 2.7 standard deviations, corresponding to a global significance of 2.5 standard deviations. This result may provide the first evidence for the Higgs coupling to b quarks and we are looking forward to the discovery of $H \rightarrow b\bar{b}$ at LHC.

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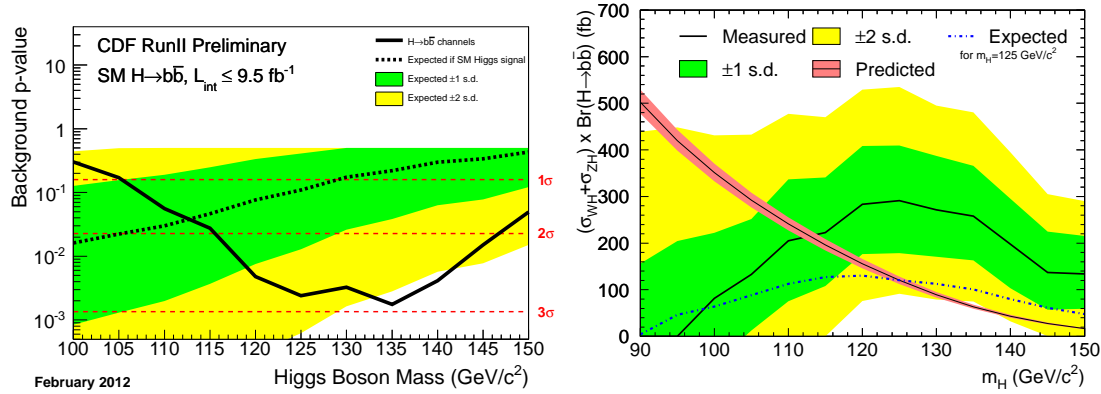


Figure 2: (Left) Background-only p-value for the combined search and the expected value assuming a SM Higgs signal is present as a function of m_H . (Right) The best-fit cross section times branching ratio as a function of m_H . The shaded regions show the one or two sigma bands and the SM prediction is shown as a smooth falling curve. The dot-dashes are what is expected for the SM Higgs signal of $m_H = 125 \text{ GeV}/c^2$.

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